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### LASER-POWERED THRUSTERS FOR HIGH EFFICIENCY VARIABLE SPECIFIC IMPULSE MISSIONS

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### ABSTRACT

Our objective is to develop an engine with high efficiency, and specific impulse which can be varied over more than an order of magnitude to match the requirements of efficient spacecraft propulsion in the constant momentum propulsion regime. Laser ablation propulsion uniquely offers an almost arbitrarily large range of exhaust velocity, since it depends only on incident laser intensity. We have shown that thrust efficiency remains good over the specific impulse range 150 to 3,200 seconds. Considering a laser ablation propulsion device as an electric thruster, use of energetic ablation fuels can give thrust electrical efficiency greater than unity at the bottom of this  $I_{sp}$  range. In our laser plasma thrusters (LPT's), we have demonstrated specific impulse which can be varied over a factor-of-15, from 200 to 3000 seconds to match the velocity profile in a mission. The corresponding thrust efficiency varies from 165% to 40%. The micro-LPT product has a 0.1 – 10 mN thrust range. After reviewing the science basis and performance of the existing devices, we describe the unique capabilities predicted for the LPT technology when it is scaled to the 1N thrust level. This scaling permits taking full advantage of the technology's inherent advantages in thrust/power ratio (up to 1.35N/kW), thrust efficiency and thrust density (5,000 to 350,000 N/m<sup>2</sup>). However, the most important capability of the "macro-LPT" design is variable  $I_{sp}$  for optimally-efficient, constant-momentum flights. Claims made for the macro-LPT are based on measured performance of our millisecond and nanosecond-pulse LPT devices, and the anticipated performance of a revolutionary liquid ablation fuel.

### TERMINOLOGY

To review this complex field, it is important to summarize its terminology.

The momentum coupling coefficient  $C_m$  is defined as the impulse  $\delta J$  created by incident laser pulse energy  $W$  (or thrust  $F$  to power  $P$  for a continuous laser signal) where exhaust velocity  $v_E = \langle v_x \rangle$  is the first moment of the velocity distribution  $f(v_x)$  along the thrust axis  $x$ .

$$C_m = \delta J/W = \delta m v_E/W = F/P \quad (1)$$

Often, this distribution will be a "drift maxwellian" of the form<sup>1</sup>

$$f(v_x, v_y, v_z) = C_x C_y C_z \{ \exp - \beta [(v_x - u)^2 + v_y^2 + v_z^2] \} \quad (2)$$

with significant Mach number  $M = u/c_s$ . Defining also specific ablation energy

$$Q^* = W/\delta m \quad (3)$$

the relationship (4)

$$v_E = C_m Q^* .$$

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offers a convenient way of determining exhaust velocity since both  $C_m$  and  $Q^*$  are easily measured. Specific impulse is related to exhaust velocity by

$$I_{sp} = v_E / g_0 \quad (5)$$

and is a useful concept in rocketry since it is also the impulse created by unit *weight* of fuel,

$$I_{sp} = \delta J / (\delta m g_0), \quad (6)$$

with dimensions N-s/N or seconds.

$$\text{Ablation efficiency} \quad \eta_{AB} = W_E / W = \delta m \psi v_E^2 / (2W) \quad (7)$$

is the efficiency with which laser pulse energy is converted into exhaust kinetic energy. It is related to the other parameters by

$$\eta_{AB} = \psi C_m v_E / 2, \quad (8)$$

$$\text{where} \quad \psi = \frac{\langle v_x^2 \rangle}{(\langle v_x \rangle)^2} = \left\{ \frac{u^2 + \frac{kT}{m_E}}{u^2} \right\} \quad (9)$$

We usually take  $\psi = 1$  because it can be shown<sup>1,2</sup> that typical ablation plume shapes correspond to  $\psi \leq 1.15$ . This choice underestimates  $\eta_{AB}$ .

Eq. 8 can be restated to show that  $C_m$  and  $I_{sp}$  form a constant product controlled by the parameter  $\eta_{AB}$ :

$$C_m I_{sp} = 2\eta_{AB} / g_0. \quad (10)$$

From  $\eta_{AB}$  and  $\eta_{eo}$ , the efficiency with which electrical energy is converted to laser energy, thrust efficiency in laser ablation thrusters can be computed,

$$\eta_T = \eta_{eo} \eta_{AB} \quad (11)$$

The product is 0.204 when  $\eta_{AB} = 1$ . With laser repetition frequency  $f$ , laser average power  $P = fW$  and the rate of mass usage is

$$\dot{m} = \frac{P}{Q^*} \quad (12)$$

When considering  $C_m$  and  $I_{sp}$  as design variables, it must be kept in mind that the ablator lifetime decreases very rapidly with increasing  $C_m$  or decreasing  $I_{sp}$ . Where  $M$  is the original ablator mass, the lifetime is

$$\tau_{AB} = 2\eta_{AB} M / (P C_m^2) = g_0^2 M I_{sp}^2 / (2 P \eta_{AB}) \quad (13)$$

For this reason, increasing  $C_m$  to get more thrust via the relationship

$$F = P C_m \quad (14)$$

from a given laser entails a serious penalty for ablator lifetime, to the point where a mission cannot be accomplished because the ablator is used up.

Some useful theory applies to the case of laser ablation propulsion. When a pulsed laser beam strikes a solid-state surface above plasma threshold fluence, which is approximately equal to the fluence for optimum momentum generation<sup>3</sup>,

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$$\Phi_{\text{opt}} = 480 \tau^{0.5} \text{ MJ/m}^2, \quad (15)$$

If the surface is a passive (i.e., non-exothermic) material, inertial confinement fusion theory allows us to derive expressions for  $C_m$  and  $I_{\text{sp}}$ .<sup>4</sup>

$$C_m = 1.84E - 3 \frac{\Psi^{9/16} / A^{1/8}}{(I \lambda \sqrt{\tau})^{1/4}} \quad (16)$$

$$I_{\text{sp}} = 442 \frac{A^{1/8}}{\Psi^{9/16}} (I \lambda \sqrt{\tau})^{1/4} \quad (17)$$

allows us to estimate  $I_{\text{sp}}$ , where  $\Psi = (A/2)[Z^2(Z+1)]^{1/3}$ ,  $A$  is the mean atomic mass number and  $Z$  the mean ionic charge in the laser-plasma plume.  $C_m$  is governed by the constant-product relation, Eq. 10.

If the surface is a volume absorber or exothermic, the theory is more complex<sup>5</sup>.

## ADVANTAGES OF LASER ABLATION PROPULSION

### LOW TOXICITY FUELS AND COMBUSTION PRODUCTS

In our Laser Plasma Microthruster, Glycidyl Azide Polymer (GAP) is the principal active ingredient, and the principal exhaust product after laser ignition is nitrogen gas.

### ADJUSTABLE SPECIFIC IMPULSE

With laser ignition, we are able to adjust exhaust velocity to the optimum value for each mission and, where needed, to achieve exhaust velocities well beyond what is possible with chemistry due to higher temperatures in laser-produced plasma. The maximum specific impulse of ordinary chemical rockets is about 500s, limited by the temperatures available in chemical reactions. For example, the heat of formation for hydrogen-oxygen combustion, one of the hottest chemical reactions, is 57.8 kcal/mole<sup>7</sup>. This translates to a reaction temperature of 2.91E4K, for which the most probable thermal velocity  $(2kT/m_E)^{0.5} = 5.17 \text{ km/s}$ , giving  $I_{\text{sp}} = 527 \text{ s}$ . In contrast,  $I_{\text{sp}}$  up to 7600s has been measured<sup>2</sup> in laser produced aluminum plasmas driven by an ordinary 20ns KrF laser. This  $I_{\text{sp}}$  corresponds to  $T = 9.1E6 \text{ K}$  (780 eV). In more recent work,<sup>8</sup> a ns-pulse laser thruster using a few mJ per pulse produced a sustained  $I_{\text{sp}} = 3200 \text{ seconds}$ . In both cases,  $I_{\text{sp}}$  was determined from mass loss of the ablative target according to Eq. 6.

### LOWER DEAD MASS

This benefit derives from not having to include turbines, pumps, tanks, exhaust nozzles, etc. in the payload.

### ENABLING OTHERWISE IMPOSSIBLE MISSIONS

A fourth advantage results from considering the previous three together in practical designs, which can yield situations in which LSP can do what no other existing thruster hardware can do. A recent "Broad Area Announcement" set the following graduate-level aerospace engineering problem<sup>11</sup>. A 180-kg spacecraft has 1kW prime power. You are allowed to design an engine whose total mass including fuel is 80kg. Its baseline orbit is at 500km altitude. The spacecraft must be able to complete any of the following four missions on demand:

- Rephase the orbit 180 degrees in 12 hours
- Raise the spacecraft from to 1500km in two days, then return to baseline in 30 days

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- Rotate the orbital plane 15 degrees in 90 days
- Drop the spacecraft to 300km, fight ram pressure for a year with only 50W prime power, then return to baseline in 30 days.

The criteria were deliberately chosen to be impossible to meet with currently fielded thruster technology. However, a laser-ablation propulsion engine using a set of diode-pumped glass fiber amplifiers with a total of 350-W optical power can accomplish all the tasks, according to our calculations.

## THE LASER PLASMA THRUSTER

**Table 1. msLPT performance**

<i>Parameter</i>	<i>Value</i>
<i>Thrust</i>	<i>0.1 – 10 mN</i>
<i>C<sub>m</sub></i>	<i>2.3 mN/W</i>
<i>I<sub>sp</sub></i>	<i>180 s</i>
<i>Ablation Efficiency <math>\eta_{AB}</math></i>	<i>205%</i>
<i>Thrust Efficiency <math>\eta_T</math></i>	<i>133%</i>
<i>Thrust/Electrical Power</i>	<i>0.5mN/W</i>
<i>Minimum Impulse</i>	<i>10nN-s</i>
<i>Volume</i>	<i>670 cm<sup>3</sup></i>
<i>Mass</i>	<i>0.5 kg</i>
<i>Electrical Power</i>	<i>20 W (max)</i>
<i>Lifetime Impulse</i>	<i>50 N-s</i>
<i>Fuel Capacity</i>	<i>44 g</i>
<i>Type of Laser</i>	<i>JDSU 6396 diode</i>
<i>Ablation Fuel</i>	<i>Glycidyl azide polymer</i>

The ms-pulse Laser Plasma Thruster<sup>12-14</sup> (msLPT) is a good example of low-power applications of laser ablation propulsion, and may be the first realization of LSP to actually fly in space [Table 1, Figure 1]. It is also the first realization of chemically-augmented electric propulsion. Among microthrusters, it excels in specific mass (20 kg/kW), thrust density (350,000 N/m<sup>2</sup>) and total thrust efficiency (133% is obviously a result that no other technology can match). This surprising value for thrust efficiency arises because  $\eta_{eo}$  (see Eq. 11) can be 65% for the latest generation of diode lasers, and  $\eta_{AB}$  values up to 205% have been measured with the exothermic polymer ablation fuels.

A substantial literature<sup>15-18</sup> exists concerning the physical chemistry and the correlation of thrust with material, plasma and shockwave properties of the exothermic polymers developed specifically for the microthruster laser

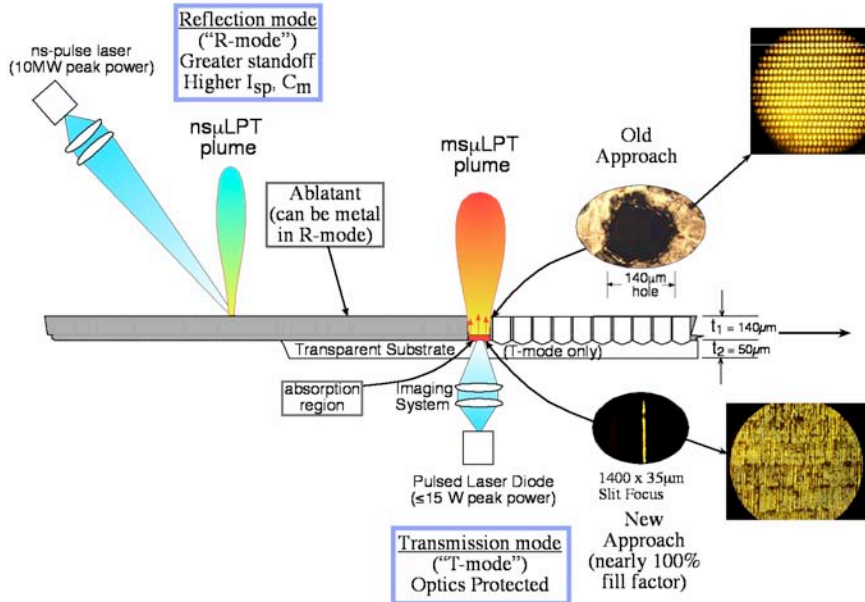
ablation fuel application.

These two units will be combined in a single device using low-mass diode-pumped glass fiber laser amplifiers to operate in either long- or short-pulse regimes at will. Adequate fiber lasers have been demonstrated<sup>19</sup>.

The principle of operation of the msLPT is illustrated in Figure 2. Reflection mode is suitable for the 1-N engine we plan to develop, as outlined in the following section. Very high  $I_{sp}$  has been obtained with ns-duration pulses. The developmental ns-pulse thruster (nsLPT)<sup>8</sup> has achieved  $I_{sp} = 3660s$  with  $C_m = 56\mu N/W$  and  $\eta_{AB} = 100\%$  [Table 2].

## SCALING CHEMICALLY AUGMENTED ELECTRIC PROPULSION TO 1N THRUST

## Microthruster Illumination Summary



**Figure 2.** Two modes of operation exist for the LPT. On the right in the figure, transmission mode utilizes a double-layer fuel tape with the laser absorber on the front. In reflection mode, suitable for the 1-N thrust engine, the fuel is a single layer and may be film, wire or a low-vapor-pressure liquid extruded from an orifice.

Technically, the ms-LPT is an example of chemically augmented electric propulsion, and there is no reason why the concept cannot be expanded to the 1N thrust range.

**LIQUID FUELS**

To do this, we need liquid ablation fuels for practical reasons. Huge reels of tape moving at the required velocity would destabilize a space platform. This can be based on the same energetic polymers we developed for our LPT fuel tapes, without polymerization. GAP has a low vapor pressure. Alternatively, we can dissolve polymerized GAP in ionic liquid solvents such as EMI-BF<sub>4</sub> (already used in electrospray thrusters), which have vanishing vapor pressure. Rather than carbon doping, we will use

infrared dyes for laser absorption.

**FIBER LASER**

To build the 1-N thruster, we also require a high power, fiber laser oscillator-amplifier system capable of 400W time-average optical power output in the ms-pulse mode. This can be an array of eight diode-pumped Yb-doped fiber amplifiers with variable pulsewidth and 50W time-average power output each channel. To obtain long-pulse operation, the lasers are not Q-switched.

**1N THRUST PROPULSION SYSTEM**

Table 2. Demonstrated technology basis		
Ablation Fuel	Gold	GAP:C
Pulsewidth	5ns	1ms
$I_{sp}$ (s)	3200	200
$C_m$	25 $\mu$ N/W	3.4mN/W
Ablation efficiency	95%	334%
Fluence (MJ/m <sup>2</sup> )	1.0	0.25

The result will be a new departure in electric propulsion systems which will dramatically enhance mission capabilities of vehicles and payloads because of its low mass. Specific impulse will be varied by changing the laser pulse width from 10ns to 1ms. The electric propulsion portion of the system will use variable pulsewidth glass fiber oscillator-amplifiers, rather than the diodes used in the  $\mu$ LPT, to achieve

Table 3. LPT Motor Parameters		
Motor $P_{in}(\text{electrical})$	1kW	
Motor Mass	20kg	
Fuel Mass	60kg	
No. of Fiber Lasers	14	
Pulse Repetition Rate	10kHz	
Fuel Type	Energetic Liquid Polymer	
	High $I_{sp}$ mode	Low $I_{sp}$ mode
Thrust	10 $\mu$ N to 7mN	1mN to 1N
$I_{sp}$	3,000s	200s
Electrical/optical Efficiency	35%	50%
Thrust Efficiency	35%	160%
Mass Usage Rate	0.6mg/s	500mg/s
Lifetime at usage rate	3.2 years	3.3 hours
Lifetime Impulse	2240kN-s	11.9kN-s
$\Delta v$ for 180kg spacecraft	12.4km/s	66m/s
<b>Fiber Lasers:</b>		
Total Optical Power	350W	400W
$P_{avg}$ (optical), EA	25W	29W
$P_{peak}$ (optical), EA	250kW	290W
Pulse Duration	10ns	1ms
Pulse Energy, EA	2.5mJ	290mJ
Pulse Repetition Rate	10kHz	100Hz

approximately 350W time-average optical power, which will produce 1N thrust at low  $I_{sp}$  and 7mN at high  $I_{sp}$ . Table 3 summarizes what we expect to achieve with the new engine.

In the Table, we assume 60kg of liquid ablation fuel, and calculated the  $\Delta v$  which would be achieved for a 180-kg spacecraft.

Note that the fuels we use are exothermic, but are not detonable.

Laser efficiency parameters listed in the Table have been demonstrated.<sup>19</sup>

## CONCLUSIONS

We have introduced the concept of chemically augmented electric propulsion, discussed real devices that we have developed with the concept, and shown how we can apply

the concept to developing a low-mass, 1N-thrust electric propulsion engine using liquid fuels. These fuels are far less toxic than the hypergolic fuels which have been in wide use for decades.

The result would weigh about 20kg and would give dramatic performance to certain types of space payloads.

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